WEAR ANALYSIS ON DIFFERENT CUSTOMIZED TWIST DRILL BIT DESIGNS IN DRILLING CFRP PANEL

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2021

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July 2021

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfilment of requirement to graduate with honours degree in

BACHELOR OF ENGINEERING

(MANUFACTURING ENGINEERING WITH MANAGEMENT)

School Of Mechanical Engineering

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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This thesis is the result of my own investigations, except where otherwise stated.

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ACKNOWLEDGEMENT

Firstly, I would like to express my deepest gratitude to ‘The Almighty God’ for giving me chance in completing my Final Year Project (FYP) thesis within the allocated time despite the challenging situation that we are all currently in due to Covid-19 pandemic.

Next, a heartfelt thanks goes to my supervisor, Ts. Dr. Muhammad Hafiz bin Hassan. Without his proper writing guidance, patience, insightful advice, brilliant suggestions and continuous support in sharing his expertise knowledge related to my project research, I do not think that I will capable to complete my thesis writing within the allocated time.

My next thanks goes to all of the academic and technical staff at School of Mechanical Engineering USM for providing continuous assistance, full cooperation and guidelines when handling the related machines in order to get the desired accurate result for my experimental project.

Lastly, I would like to express my final gratitude to my beloved parents (Hashimi bin Mohd Kassim and Rosni binti Man) for their continuous support and insightful advices which is really meaningful for me in order to go through this hectic last semester. Not to forget, my siblings, friends and those who have directly and indirectly involved to the completion of this final project. Once again, thank you so much to all.

Nur Hatin Raihana Binti Hashimi

August 2021

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LIST OF SYMBOLS

Ra	Hole surface roughness
f	Feed rate
F_{tmax}	Maximum thrust force
v	Spindle speed
A_{nom}	Nominal area
A_{max}	Maximum area
F_d	Delamination factor

LIST OF ABBREVIATIONS

CFRP	Carbon fiber reinforced polymer
UD CFRP	Uni directional carbon fiber reinforced polymer
GFRP	Glass fiber reinforced plastic
CFRP/TI	Carbon fiber reinforced polymer with titanium stack
CFRP/AL	Carbon fiber reinforced polymer with aluminium stack
US	Ultrasound technique
CT	Computerized tomography technique
LOM	Light Optical Microscopy
TIAIN	Titanium aluminium nitride
CVD	Chemical vapor deposition
HSS	High speed steel
PCD	Polycrystalline diamond
CNC	Computer numerical control
SEM	Scanning electron microscope
CAM	Computer aided manufacturing
G-CODE	Geometric code
BUE	Build-up edge
BUL	Build-up layer
W	Tungsten
B	Burnishing
SB	Subland drill reamer
TW	Tapered web

ANALISA KEHAUSAN PADA MATA GERUDI PUTAR YANG BERBEZA REKA BENTUK DALAM PENGGERUDIAN PANEL CFRP

ABSTRAK

Penggerudian adalah sejenis teknik pemesinan yang digunakan dalam industri penerbangan terutamanya bagi pembuatan bahagian dan struktur pesawat dengan menggunakan mata gerudi sebagai alat pemotong dan lamina komposit CFRP sebagai bahan kerja. Penggerudian masih dianggap sebagai salah satu proses yang paling mencabar kerana isu-isu yang kerap berlaku seperti kecacatan delaminasi dan juga kehausan alat yang cepat yang pada akhirnya menurunkan kualiti lubang yang dihasilkan. Salah satu sebab yang membawa kepada masalah seperti itu adalah kerana ketidaksesuaian antara alat pemotong yang digunakan dan juga komposit yang dihasilkan. Kajian ini menganalisa kehausan pada reka bentuk bit gerudi putar yang berbeza yang disesuaikan dalam penggerudian panel CFRP. Ianya disiasat berdasarkan corak daya tuju dan bentuk suhu ketika menggerudi lubang pemesinan yang berbeza dengan menggunakan tiga alat pemotong yang berbeza iaitu burnishing (B), subland drill reamer (SB) dan juga web drill bit (TW). Tujuannya supaya pengeluar dapat tetap waspada dengan mengubah bit gerudi mereka jika daya tujah dan nilai suhu yang diperoleh lebih dekat dengan nilai yang menyebabkan alat pemotong memakai. Parameter pemesinan yang digunakan dalam kajian ini adalah tetap kerana penggerudian berlaku hanya pada kelajuan gelendong 3000 rev/min dan kadar suapan iaitu 0.05 mm/rev. Hasil yang diperoleh kemudian ditabulasikan dan dianalisis dengan justifikasi yang tepat sebelum sampai pada kesimpulan akhir.

WEAR ANALYSIS ON DIFFERENT CUSTOMIZED TWIST DRILL BIT DESIGNS IN DRILLING CFRP PANEL

ABSTRACT

Drilling is one of the most common machining technique being practiced in the aviation industry especially during the fabrication of aircraft parts and structures by using twist drill as the cutting tool and CFRP composite laminate as the workpiece. However, drilling is still consider as one of the most challenging process as these recent issues lead to the occurrence such as delamination defect and also rapid tool wear which in the end degrade the hole quality produced. One of the reasons that lead to such issues might be due to the incompatibility between the cutting tool used as well as the composites manufactured. Therefore, in this study, wear analysis on different customized twist drill bit design in drilling CFRP panel are being investigated. It is based on the thrust force signature and temperature form when drilling different machining holes by using three different cutting tools which are burnishing (B), subland drill reamer (SB) and also tapered web drill bit (TW). The purpose is so that manufacturers can stay alert by changing their drill bit if the thrust force and temperature value obtained is nearer to the values that cause wear cutting tool. The machining parameters used in this study is constant as the drilling take place at 3000 rev/min spindle speed and 0.05mm/rev feed rate. The results obtained were then tabulated and analyzed with proper justifications before reaching to the conclusion.

CHAPTER 1

INTRODUCTION

1.1 CFRP material in aerospace industry in general

Carbon fiber reinforced polymer (CFRP) has become one of the highly regarded composites used in many industries such as automotive, aerospace, civil engineering, oil and gas and sporting goods. However, among all industries, aerospace industry can be categorizing as industry that most frequently utilize CFRP composite especially in the fabrication of airplane structure in order to make it safer, more economical and sustainable, fuel efficiency and high performance aircrafts (Safri *et al.*, 2014).

Basically, CFRP is a strong and durable composite material. Carbon fiber function to provide stiffness and strength to the composite while polymer provide a cohesive matrix in order to hold and protect fibers together. Hence, providing some toughness properties to the composite as well. CFRP are fabricated in form of CFRP laminate and CFRP sandwich for application on aircraft structures. Production method such as hand lay-up processes, hot pressing method and autoclave can be used to manufacture CFRP sandwich and CFRP laminate. Usually, there are about 50 percent composition of CFRP laminate and CFRP sandwich mainly on fuselage (body parts), wings and tail of the aircraft, 20 percent of aircraft's wings and tail are made of aluminium alloy (AL), 15 percent of aircraft's wings are composed of titanium alloy (TI), 10 percent of the wings and tail structure are from steel while another 5 percent are composed of another composites. Example of the aircrafts that utilize CFRP as the main material replacing aluminium in airliners fuselage application are like the Boeing 787 Dreamliner and Airbus A350 XWB (Quilter, 2004; Smith, 2013; Zhu, Li and Childs, 2018).

CFRP also has many superior properties or performances such as high strength and stiffness, lightweight material (low density), good corrosion, chemical, temperature and vibration resistance, high fatigue resistance (less maintenance needed), low thermal conductivity, short resin curing time (reduce project application duration) and high ultimate strain. In aerospace industry, lightweight material is one of the significant consideration in material selection to be utilized in aircraft structure fabrication. It is because the material's weight can greatly influence fuel consumption of an aircraft in the future. The lighter the plane, the lesser volume of fuel needed to fly at a greater distance. Hence, saving cost as there is fewer or no refuelling stops for fuel consumption.

Besides, CFRP also does not corrode, weaken or react easily to chemical reaction or temperature changes as this composite possessed a very good corrosion, chemical, temperature and fatigue resistance properties. Therefore, less maintenance needed (saving cost as well) and the composite's lifespan also will become longer. Furthermore, CFRP also has an excellent strength-to-weight ratio due to high tensile strength, stiffness and rigidity properties. Hence, possessed incredibly resistant to breakage under tension or impact that can improve accident survivability. Thus, based on the properties and performance capability listed above, CFRP have been selected as the most widely used composite in aerospace industry compared to aluminium as CFRP possess more benefits and greater potential to be utilize in airplane structures such as fuselage (body part), wings, tail and other parts as in Figure 1.1 below. (Ozkan, Gok and Karaoglanli, 2020).

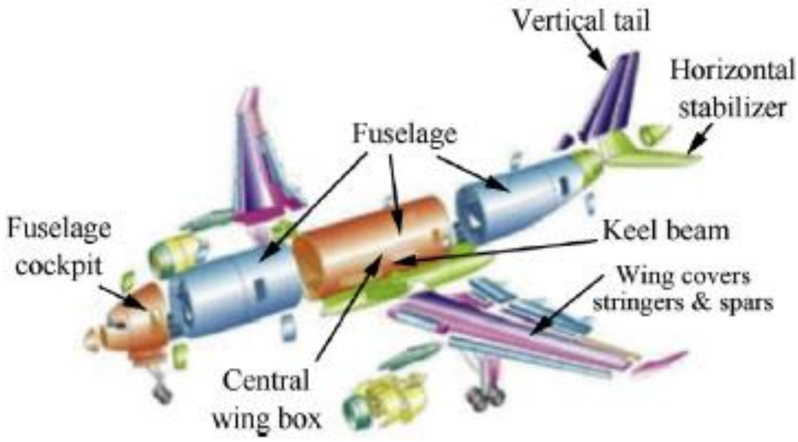


Figure 1.1 CFRP composite components used in Airbus 350 (Altin Karataş and Gökkaya, 2018).

Drilling is a cutting operation that utilize a rotary cutting tool known as drill bit in order to cut a hole of circular cross section in a solid material. The removal process method are widely used in various industries especially in the aerospace industries specifically in the fabrication of aircrafts. Hence, it is very necessary to ensure that the machining parameters setup and cutting tool condition are in good control so that the quality of the holes formed satisfy the specifications or requirements of the holes tolerance as stated by the aerospace industry.

1.2 Research Background

In machining of carbon fiber reinforced polymer (CFRP), drilling can be consider as the most used process in aircraft industry. According to (Jugrestan *et al.*,(2017), acoustic panels capable to produce up to 100,000 holes when drilling. Therefore, it is very significant to select the right cutting tools with excellent mechanical characteristics and properties, drilling methods and drilling parameters used also are correctly adjusted and setup in order to make sure that the holes formed satisfy the hole tolerances as stated by the aircraft industry.

Due to its excellent properties, CFRP are widely used in aerospace industry. This is because more than 50% of the materials' composition used to build the aircraft are made of CFRP material. CFRP also offer superior properties such as damage tolerance, fatigue resistance, strength-to-weight characteristics (good strength and lightweight material), corrosion resistance, high stiffness and durability (Gaugel *et al.*, 2016; Fernández-Pérez *et al.*, 2019). However, there are some problems that possible to occur when drilling CFRP composite such as delamination cracking, rapid tool wear, thermal degradation of the underlying matrix, peeling, fiber pulling out, fibers projection, uncut fibers, pyrolysis and hole surface damage (Jugrestan *et al.*, 2017; Kuo, Wang and Ko, 2018; Fernández-Pérez *et al.*, 2019). This is due to the characteristics of CFRP composites which is anisotropy, high abrasiveness and non-homogeneity and also probably occur due to unsuitable cutting tools geometry, unsuitable cutting parameters used and also the condition of the tool used such as tool wear (Jugrestan *et al.*, 2017; Kim, Nam and Lee, 2019). Hence, lead to the possible defects as stated above which in the end affecting the integrity of the composites structure, reducing the composite's resistance against fatigue and resulting to the poor assembly tolerance due to the degradation of tools (rapid tool wear).

Based on the studies carried out by previous researchers, the study show that abrasive wear, adhesion and chipping are tool wear mechanisms in drilling of composite materials. The magnitude of tool wear also are more sensitive to the cutting speed, feed rate and thrust force applied. This is because high values of cutting speed, feed rate and thrust force applied can cause the wear rate of the tool to become rapid as well. In the end, resulting to larger size of delamination damage occurrence onto the CFRP laminate which can result to degradation in the hole quality produced and inaccurate hole diameter produced (Gaugel *et al.*, 2016). As the cutting speed increases, there is also high chance for flank wear to occur. This is mainly due to the abrasion of carbon fibers when drilling CFRP (Raj and Karunamoorthy, 2018). Therefore, it is very significant to make the right tool selection wisely, choose appropriate tool condition and tool geometry, adjust machining parameters like cutting speed, feed rate and thrust force optimally so that any possible damage that might occur on the specimen surface which able to disrupt the hole quality or might degrade the tools quality can be avoided from occur.

Thus, this study will identify wear analysis on different customized twist drill bit design in drilling CFRP panel. The main aim is to identify the relationship between machining parameters and the tendency for the tool wear to get worsen during the machining process. Setting appropriate machining parameters such as optimum temperature, thrust force, cutting speed, feed rate and others are very significant in order to produce accurate and better hole quality while at the same time maintaining good condition of cutting tool with low tendency to wear (longer cutting tool life) after drilling process finished.

1.3 Problem Statement

Previous study in carbon fiber reinforced polymer (CFRP) proved that characteristics of CFRP such as high abrasiveness, stiffness, anisotropy, non-homogeneity and heat sensitive matrix cause the machining process to become more challenging (Gaugel *et al.*, 2016; Kim, Nam and Lee, 2019). This is because abrasiveness properties of carbon-fiber rapid the tendency for the tool wear to occur. As the effect, hole quality is reduce and hole diameter produce is inaccurate as the result from using tool which is wear when machining. Besides, high thrust force and high temperature also can contribute for the tool wear to occur or worsen from the current tool state. High thrust force can cause the vibration during drilling to increase while high temperature during drilling can result to damage in the epoxy. Hence, reducing the overall strength of the composite structure. This will also lead to the formation of other damages on the hole such as fiber pull-out, surface burning, delamination, micro-cracks on the entry or exit side and matrix melting. When machining at high temperature, there is also high tendency for the tool wear to become worsen at the cutting lips. This is due to continuous friction between blunt cutting tool usage and the workpiece which in the end can disrupt the whole performance of the drilling operation.

Once the tool wear occur, it cannot be eliminated. However, the tool wear can be reduce by selecting proper cutting parameters that fit well with the CFRP specimen and able to maintain current tool state from becoming worsen (progressive wear)(Dogrusadik and Kentli, 2019). Therefore, continuous research for wear analysis on different customized twist drill bit designs in drilling CFRP panel is very relevant and necessary in order to discover the exact temperature and thrust force that can lead to damage in hole quality due to wear drill bit usage.

1.4 Objectives

The main objective of this research is to analyse the value of thrust force and temperature that can contribute to tool wear in drilling the composite. The purpose is so that manufacturers can stay alert with the values obtained by changing the drill bit frequently so that good hole quality can be produced by the end of the drilling operation. Thus, in order to achieve this main goal, the specific objectives were listed as below:-

1. To identify the relationship of worn bit of different type to the thrust force and temperature during drilling CFRP panel.
2. To discover the effect of the worn bit to the hole integrity of the composite panel when drilling a single shot process.
3. To identify the percentage of the increment of the thrust force and drilling temperature between fresh drill and worn drill.

1.5 Scope of work

In this project, unidirectional type CFRP panel (UD CFRP) is chosen as the based material for work pieces while three cutting tool or drill bit made up of tungsten carbide are given for drilling. The CFRP composite specimen consists of 26 unidirectional plies of 0.125mm thickness each, making the total laminate thickness of 3.25mm. The purpose of choosing material made up of tungsten carbide as cutting tool is because tungsten carbide are very stiff, have high modulus elasticity and good wear resistance.

Hence, leading to good economic performance and accurate result outcome (Fernández-Pérez *et al.*, 2019). The size for all three bits are the same which is 6.35 mm. These three bits are categorized under twist drill type. However, the design or tool geometry for each bit are quite different. All of the drill bits that involve in this project are known as burnishing drill bit (B), sub-land drill reamer drill bit (SB) and tapered web drill bit (TW).

The primary goal of doing this project is to analyse the effect of worn drill to the CFRP panel at the constant drill parameter which is 3000 rev/min of spindle speed and 0.05 mm/rev of the feed rate. Besides, this research also would discover the exact cutting temperature and thrust force that lead to the poor hole quality produced due to the worn drill bit. Lastly, it is to compare the thrust force result from fresh drill and wear drill after drilling CFRP panels.

CHAPTER 2

LITERATURE REVIEW

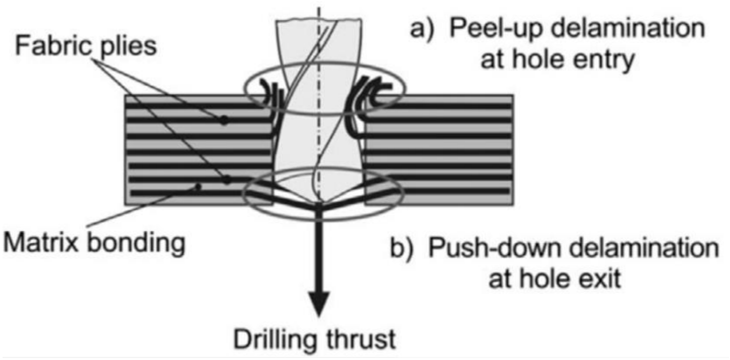
2.1 Introduction

Recently, composite material such as carbon fiber reinforced polymer (CFRP) are widely used in automotive, aeronautics and aerospace industry especially during the fabrication of structural components compared to other metal alloys such as aluminum, steel, titanium and others. Example of structural components that utilized CFRP composite laminates are like in wing panels, wing boxes, vertical stabilizers, horizontal stabilizers, tail part, passenger compartments, fairings, storage room doors and landing gears doors (Quilter, 2004). This is highly due to CFRP excellent mechanical properties which are high stiffness and strength, lightweight (low density) material, high damage tolerance, good fracture resistance, good corrosion resistance, high toughness and durability, lower maintenance control surface, good environmental resistance, excellent fatigue resistance, high strength-to-density ratio and also high energy absorption (Gómez-del Río *et al.*, 2005; Safri *et al.*, 2014; Liu, Zhuang and Wu, 2020).

Machining process such as drilling operations are widely used for assembly purposes especially in assembling mechanical parts together with the aid of screws. However, there are some challenges or complexity that the manufacturers faced during the drilling operation which commonly involving CFRP, GFRP, CFRP/Ti stack, CFRP/Al stack and others. The difficulties are mainly due to the incompatibility between cutting tools used and also the composite materials used as the specimen. This is because the composite materials might have low machinability (tend to fracture when drill at certain limit) and incapable to be drilled based on the quality specifications and tolerances as requested by the industry. The tool also might tend to rapid quickly due to the anisotropy, high abrasiveness, non-homogeneity and heat sensitive matrix workpiece material such as CFRP. Hence, can lead to defects such as delamination or chipping deposited during drilling which in the end can disrupt the hole quality formed (Fernández-Pérez *et al.*, 2019). Therefore, it is very significant to choose appropriate tool condition and tool geometry wisely, select material that capable to withstand range of thrust force and high temperature exerted by the cutting tool during drilling, adjust machining parameters like cutting speed, feed rate and thrust force optimally so that any possible damage that might occur on the specimen surface which able to disrupt the hole quality or might degrade the tools quality can be avoided from occur.

Delamination is one of the most frequent damage that occur during drilling operation of composite specimen. Generally, delamination is define as the separation of adjacent composite plies into multiple layers based on the formation of interlaminar cracks in the composite material. This defect usually occur on the hole entrance (peel-up delamination) and also hole exit-side (push-down delamination). Delamination usually occur due to wear cutting tool usage during drilling. Hence, contribute to increase in thrust force exerted on the workpiece. When the thrust force value applied during drilling increases, the vibration incur also will become increases. In the end, lead to larger delamination size on the drilled hole result (disrupt the hole quality, hole diameter, hole circularity and hole surface roughness). In order to observe and evaluate the damage formed around the holes, techniques such as ultrasound techniques (US), X-ray radiography, computerized tomography (CT) and light optical microscopy (LOM) can be utilized (Gaugel *et al.*, 2016). The schematic illustration of delamination damage during the drilling process can be seen as in the Figure 2.1 (a) below while Figure 2.1 (b) show the numerical simulation for effect of drill bit on delamination at hole entrance and hole exit. In order to avoid delamination failure from occur, it is highly recommended to use coating on the cutting tool such as TiAIN-coated carbide drill or diamond-coated carbide drill in order to reduce the tendency for the tool from wear rapidly. Besides, it is also important to always change the tool used after drilling for a certain period of time to a sharp cutting tool. Thus, delamination can be prevented and hole quality result that fulfil the tolerance desired as stated by the industry can be produced (Ozkan *et al.*, 2020).

(a)



(b)

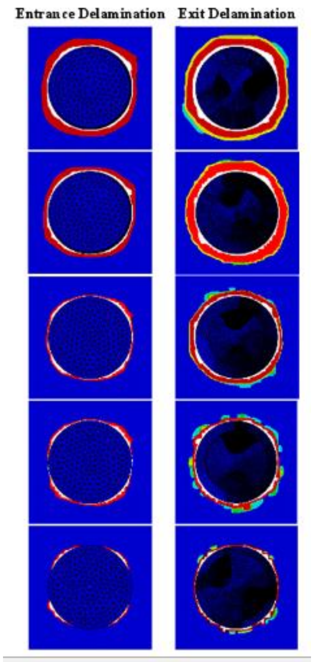


Figure 2.1 (a) Schematic illustration of delamination damage during drilling operation, (b) Numerical simulation for effect of drill bit on delamination at hole entrance and hole exit (Isbilir and Ghassemieh, 2013; Gaugel et al., 2016).

2.2 Drilling for CFRP composite

Due to properties of CFRP material which is heterogeneous and anisotropic, it is quite complex to drill the composite without proper cutting tool material selection and proper machining parameters setup. This is because the anisotropic structure and heterogeneous characteristic of CFRP composite can lead to overheating occurrence, fibers ripping from matrix, high shearing force, delamination and also contribute to defects occurrence in the surface quality outcome (Muhamad Khairussaleh, Che Haron and Ghani, 2016) if improper cutting tools material selection were made. Machining CFRP also can cause rapid tool wear, tool edge chipping and excessive abrasive wear on tool edge as the result of machining high strength carbon fibers. As the cutting time increases, the tool's sharpness will become reduce and tend to be blunt. This is due to the continuous friction exerted between specimen and cutting tool during drilling. Thus, thrust force and temperature will become increases as well due to extreme thermal and mechanical stresses imposed on the cutting tool. In the end, contribute to rapid tool wear which can affecting the dimensional accuracies and outcome of the surface quality (Azmi, 2015). Therefore, it is very significant to identify and analyse drilling parameters that are still within acceptable limits and range for both specimens and cutting tool to continue the drilling operation. The purpose is so that any potential defects that might occur onto the specimen as well as degradation of tool due to rapid tool wear can be avoided from occur. By referring table below, manufacturer can stay alert by changing the drill bit from time to time once the drilling parameters are nearly to overlimit the range stated so that any undesirable defects that can disrupt the hole quality outcome and also cause rapid tool wear or even worst can cause tool breakage can be avoided from happening in the future. Table 2.1 show that most researchers such as Xu et al, Kuo et al, Wang et al, Perez et al and Khairusshima and Sharifah are focusing on the feed rate which range between 0.0175-0.25mm/rev and maximum thrust force between 90-350N. These researchers also prefer to choose high quality tool which is made up of TIAIN coated carbide drill and diamond-coated carbide drill, CVD-diamond coated tools, tungsten carbide (pure or coated with other material) in order to drill the specimens with desirable hole quality and longer tool life.

Table 2.1 Summarize of drilling parameter in drilling CFRP composite

Author	**Tool material**	**Tool diameter, mm**	**Cutting speed, rev/min**	**Feed rate, mm/rev**	**Maximum thrust force, N**	**Surface topography**
Xu et al., (2020)	TIAIN-coated carbide drill & diamond-coated carbide drill	6	12000	1. 0.025 2. 0.050 3. 0.075 4. 0.100	1. 90-150 2. 60-130 3. 140-290 4. 60-130	1. flank face (dry cutting), 2. smooth cutting edge with little adhered fragments (MQL)
Kuo et al., (2018)	CVD-diamond coated tools	6.35	1. 50 2. 75	1. 0.05 2. 0.10 3.0.15	1. 70-110 2. 80-130	1.multi-facet drill-abrasion wear along the cutting lips for all three facets, chipping and microcracks 2. double-point drill-fatigue ruptures
Wang et al., (2020)	Tungsten carbide	8.53	1. 9 2. 60	1. 0.1000 2. 0.0175	1. 50-187.5 2. 100-250	1. Titanium-Ti-adhesion 2.CFRP-abrasive wear 3. Ti/CFRP stacks-abrasive wear
Gaugel et al., (2016)	Uncoated & diamond coated tungsten carbide	6	94	0.07	-	1. Uncoated carbide (twist drill)- abrasive wear 2.Coated drill- Chip-off, excessive coating fracture, abrasive wear
Azmi., (2015)	K20 helical carbide tool	12	1. 110 2. 150 3. 190 4. 230	1. 0.16 2. 0.24 3. 0.32 4. 0	-	Flank wear
Raj & Karunamoorthy., (2018)	Uncoated carbide & solid carbide drill with CVD diamond coating	6.35	60	0.15	-	-

Dogrusadik & Kentli., (2019)	Uncoated cemented tungsten carbide	0.5	1. 20000 2. 30000 3. 40000	1. 0.003 2. 0.005 3. 0.007	-	-
Hrechuk et al., (2018)	Uncoated & CVD-diamond coated carbide drill	8	100	0.02	1.175-287.5 2.172-230 3.125-175	Flank wear on the flank surfaces
Perez et al., (2019)	Tungsten carbide with diamond coating	9.54	50	0.10	1. 100-900 2. 150-350	-
Perez et al., (2021)	Carbide drill bit coated with diamond	4.825	1. 330 2. 390 3. 604 4. 620	1. 0.10 2. 0.12 3. 0.14	1. 50-300 2. 50-255 3. 50-225	1. Irregular flank wear 2. Coating breakage 3. Severe carbide abrasion, coating breakage
Celik et al., (2015)	SIAION & Wc-Co drilling tools	10	20000	0.05	1.180-750 2.200-650 3.150-600 4.100-200	-
Khairusshima & Sharifah., (2017)	Two flute solid uncoated carbide end mills	8	-	0.125-0.25	-	Abrasive wear- shiny surface on tool

2.3 Type of FRP composite material

Carbon fiber-reinforced polymer (CFRP) composite materials are commonly used in various areas such as automotive, construction, space and aviation, marine vehicles, military and others. This is due to the superior properties of this composite which are high strength and stiffness, high fatigue resistance, high wear resistance, high corrosion resistance, lightweight material and others. Due to its special properties which is excellent strength to weight ratio, utilization of CFRP composite in the fabrication of structural parts of airplane also aid in reducing overall weight of the aircraft body while at the same time have a great resistance towards external impact due to its high strength and rigidity properties. When the weight of the aircraft body is reduce, the lift force needed in order to bring the plane upwards will be reduce as well. This will also improve the overall performance of the airplane as it will capable to fly faster, higher and farther due to lightweight material usage in the structural and parts' fabrication. Hence, reducing the emissions, improving the fuel efficiency (low fuel consumption), reducing the weight of the structural components and load bearing capacity of the airplanes (Altin Karataş and Gökkaya, 2018; Ozkan et al., 2019). CFRP consist of two main components namely as the reinforcement and matrix (refer to Figure 2.2). Reinforcement usually is the fibre act as the major load-bearing element that provide high strength, rigidity and stiffness to the composite. On the other hand, matrix such as resin act as load transfer elements which enclose, hold and maintain the fibre in fixed and proper orientation plus protecting the fibre against harsh external conditions such as heat, humidity and moisture (Aleksendrić and Carlone, 2015; Tiwari, Alenezi and Jun, 2016; Altin Karataş and Gökkaya, 2018; Nikbakht, Kamarian and Shakeri, 2019) .

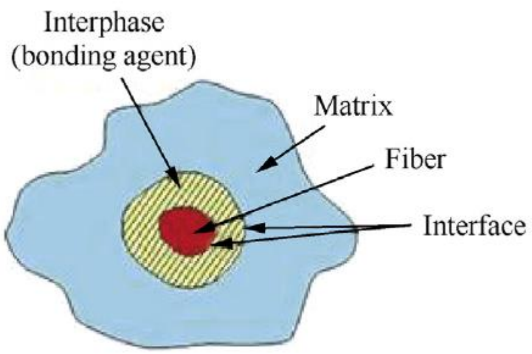


Figure 2.2 Schematic illustration for schematic structure of CFRP composite (Altin Karataş and Gökkaya, 2018).

CFRP composite material can be divided into two type which are unidirectional type and bidirectional type. In unidirectional type, the fibers only run in one direction. The strength and stiffness also is only in the direction of the fiber. Thus, it can be consider that unidirectional type have high strength in fiber direction but no strength at all across the fibres. The resin hold the fibres in place. Unidirectional type (tape) have greater strength than the bidirectional type (woven fabrics). Example of a unidirectional ply orientation is a pre-impregnated (prepreg). Prepregs are composite materials in which a reinforcement fibre is pre-impregnated in a certain ratio with a thermoplastic or thermoset resin matrix like epoxy. Many aerospace prepreg materials are impregnated with epoxy resin and cured at temperatures of 250°F or 350°F. An autoclave, oven, or heat blanket is used to cure prepreg materials. As they are cured at high temperatures and pressures, prepregs have special features and unique properties such as extremely stiff and lightweight, highly durable and temperature resistant. Unidirectional type are widely used in flat panel application. On the other hand, bidirectional type allow the fibers to run in two directions, usually 90˚ apart. These ply orientations have strength in both directions. Nevertheless, the strength value is not necessarily the same. Bidirectional type are commonly used in order to fabricate complex aerospace structures or parts which require higher fabric's flexibility in order to form the desired shape. Woven type also can help to reduce resin void size, maintaining fiber orientation during the manufacturing operation and also help to save weight. Example of bidirectional ply orientation is a plain weave fabric (Altin Karataş and Gökkaya, 2018). The laminated structure of unidirectional and bidirectional CFRP composite are illustrated as in Figure 2.3 while Figure 2.4 show the image of unidirectional fibre and bidirectional fibre orientation ply with quasi-isotropic laying up sequence of unidirectional CFRP composite laminates.

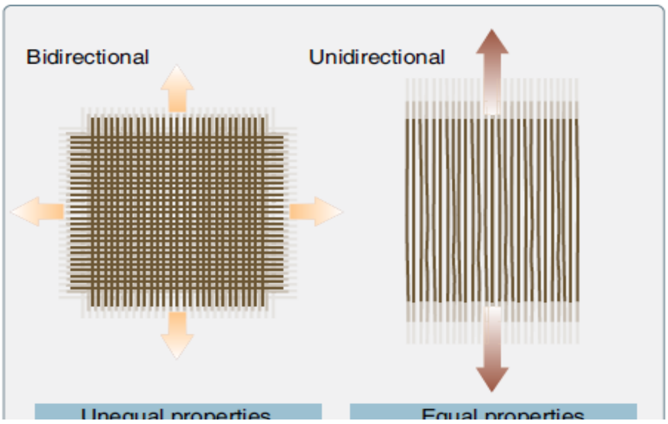


Figure 2.3 Laminated structure of unidirectional and bidirectional type of CFRP composite (Altin Karataş and Gökkaya, 2018).

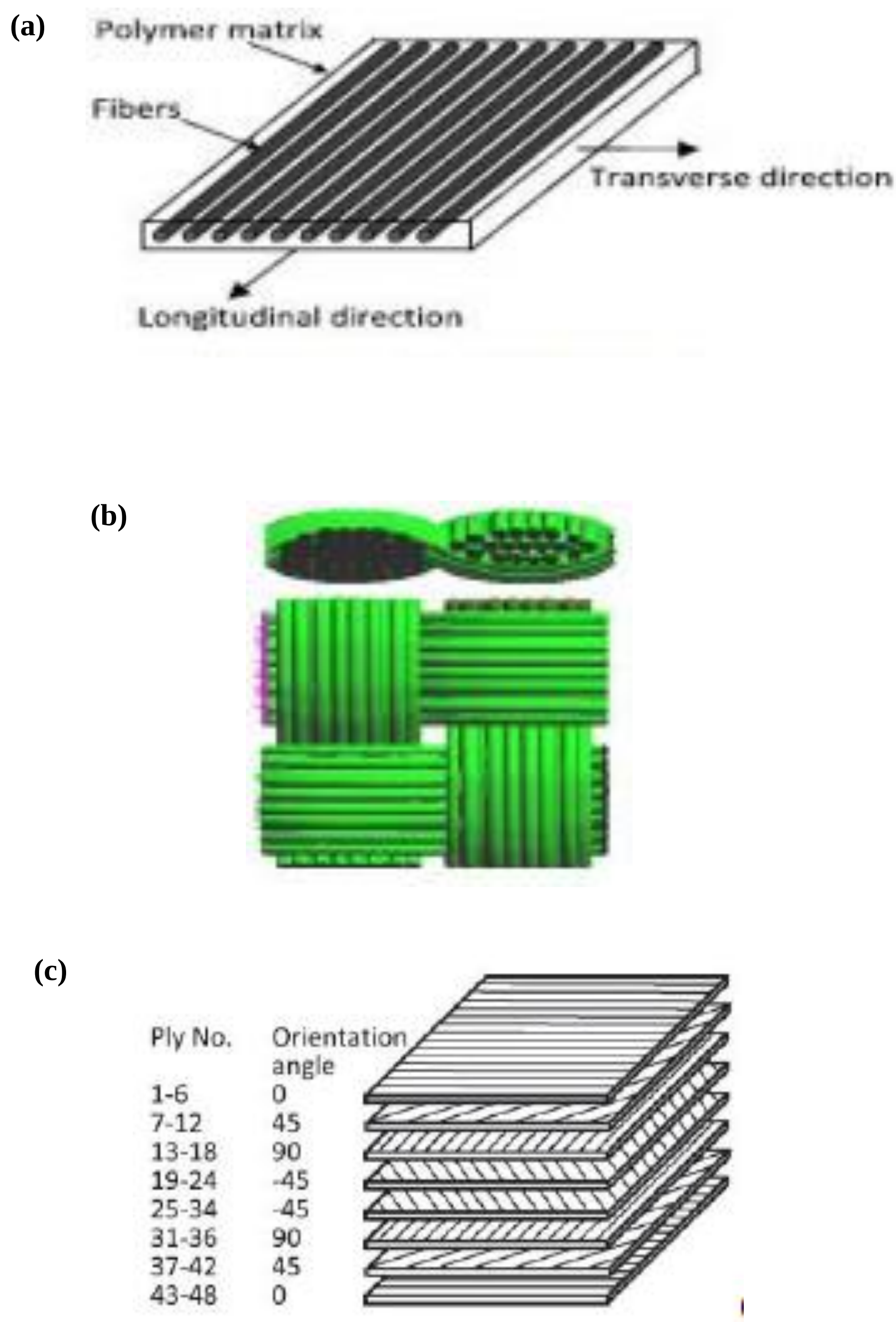


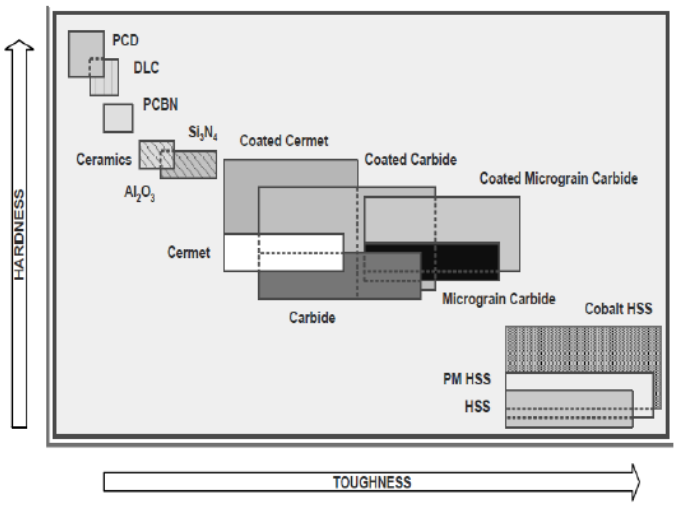
Figure 2.4 (a) Unidirectional fiber orientation ply, (b) Bidirectional fibre orientations ply (woven-ply) (c) A typical quasi-isotropic laying up sequence of unidirectional plies FRP composite laminates (Ismail *et al.*, no date; Thakur, Teli and Lad, 2019)

2.4 Aircraft drill bit material

The tool life is mostly determined by its toughness, hardness, wear resistance and thermal resistance. A good drill should be able to withstand wear, fracturing and fast rupture while maintaining hardness at high temperature. Uncoated cutting tools are usually subjected to extensive wear during the drilling process due to CFRP composite properties which are low thermal conductivity, abrasive nature, low homogeneity and anisotropic properties. CFRP composite is also consider as one of the hard-to-cut materials and quite challenging in machining operation.

Most significant criteria to be consider for cutting tools material selection are toughness and hardness. Toughness is a fundamental material property which measure a material's capability in absorbing energy and sustain shock through plastic deformation before reaching fracture phase. Material's toughness is usually measured based on capability of the material to endure shock load and cracking due to vibration during the drilling operation. Meanwhile, hardness is ability of a material to resist and withstand localized permanent deformation which is usually causes by indentation. Material's hardness are usually measured based on the capability of the material to maintain high hardness even though drilling at high temperature (Ozkan *et al.*, 2019).

(a)



(b)

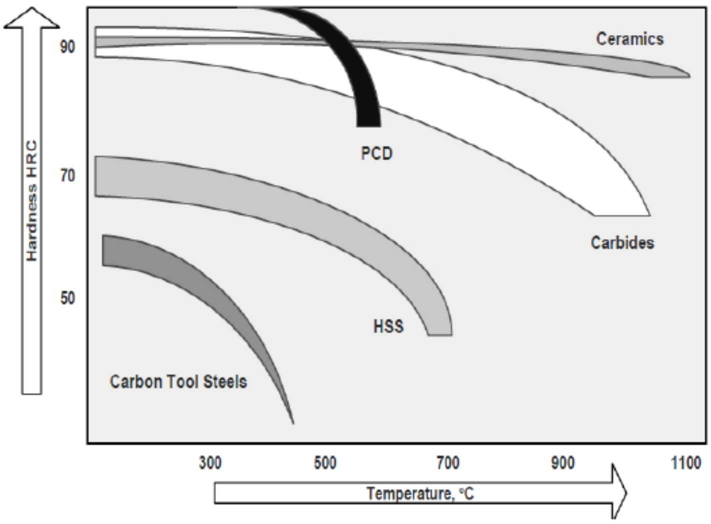


Figure 2.5 Relationship between (a) hardness of drill materials and temperature (b) hardness of drill materials and toughness of drill materials (Ismail *et al.*, no date).

By referring to Figure 2.5 (a) and (b), it can be seen that polycrystalline diamond (PCD) is the hardest tooling material and possesses least toughness property. This is because at a temperature of 600˚C, PCD facing sharp deformation phase. On the other hand, high-speed steel (HSS) possesses the best toughness properties and started to deform at 700˚C compared to other tooling materials (Ismail *et al.*, no date). Polycrystalline diamond (PCD) tools are commonly used in the fabrication of CFRP composite as this tools have high hardness. However, in terms of cost, PCD tools are very expensive. Thus, cemented carbide tools are commonly used in order to cut CFRP specimen so that the tool costs can be reduce. Nevertheless, carbide tools are tougher than diamond tools and have low hardness. Hence, other initiative that can be suggested is by coating the cutting tool with hard coating such as diamond coating so that the surface hardness, wear resistance, corrosion resistance and oxidation resistance of the cutting tool as well as surface quality of drilled composites can be increase. Carbide tools outlast other materials in terms of tool life especially if carbide grades of fine grain size are utilized.

2.5 Tungsten carbide

Tungsten carbide is a non-natural inorganic substance made up of tungsten (W) and carbon (C). It is made by heating powdered tungsten with carbon black in the presence of hydrogen at temperatures ranging from 1400˚C to 1600˚C. Mono-tungsten carbide (WC) which is stable at room temperature has hexagonal structure which consist of a grid of tungsten and carbon.

In manufacturing operation, the powdered tungsten carbide is usually mixed with another powdered metal like cobalt. The mixture was then undergo sintering process where it is press into the necessary shape. The mixture is then heated to temperatures between 1,400 and 1,600 degrees Celsius. At this point, with the grains of tungsten carbide, Cobalt powdered metal melts, wets, and partially dissolves. As a result, it acts as a binder or cement which holds the tungsten carbide together. Tungsten carbide has excellent surface resistance to galling (adhesive wear) and welding, as well as good corrosion-wear resistance for many applications. Tungsten carbide also has a high density and high melting point, strong electrical and thermal conductivity values and high hardness similar to metal. The SEM image of tungsten carbide in optimum temperature can be seen as in Figure 2.6.

Tungsten carbide capable to maintain sharp cutting edge after drilling multiple holes. It also has higher wear resistance than steel as tungsten carbide can last up to 100 times longer than steel before wears up in such condition like abrasion, galling and erosion. Thus, make it to become highly preferable in drilling operation due to its properties and capabilities in producing good surface finish with lower tool wear rate (Carbide *et al.*, 2011; Rizzo *et al.*, 2020).

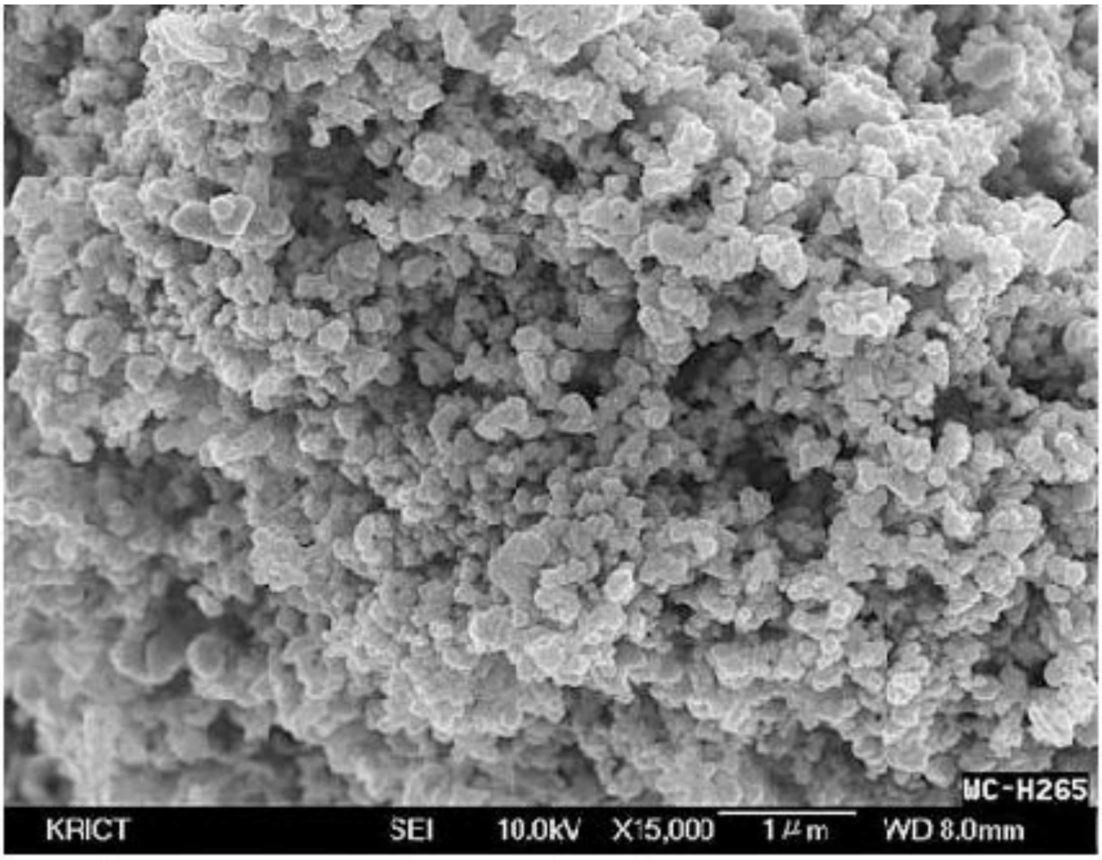


Figure 2.6 SEM image of tungsten carbide from optimum temperature
(Won, Nersisyan and Won, 2010).

2.6 Delamination

Delamination is a failure mode which commonly occur at the entrance and exit planes of the composite material whereby reinforced fibre plies separate either due to peel up delamination or push-down delamination (refer to Figure 2.7). Peel-up delamination refer to the drill progress where the material's upper layer tend to be pushed through the cutting faces of the drill instead of being cut. On the other hand, push-down delamination refer to the compressive forces that the drill bit exert causing indentation effect to the uncut laminate plies (Marques *et al.*, 2009). This defects usually occur on the drill bit's tip which pushes the bottom layers of the laminate or on the upper most layer of laminate from the rest of the body. In drilling operation, delamination defect usually occur when the drill tip applies compressive thrust force which is larger than the interlaminar fracture toughness of the layers but unable to cut the composite laminate plies. Thus, lead to poor assembly tolerance, reduce composite dimensional precision and poor structural integrity which in the end affecting the surface quality. Delamination is also influenced by variety of factors such as composite fibre nature which is abrasive and heterogeneous structure, tooling geometry, drilling parameters and also laminate orientation(Ismail *et al.*, 2017).

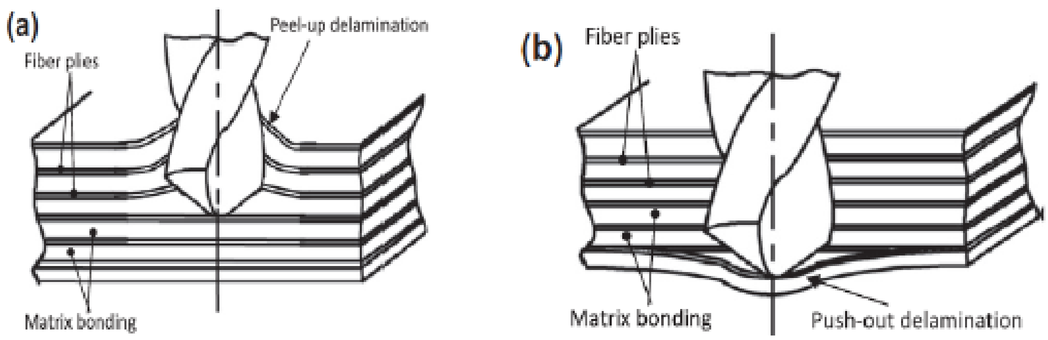


Figure 2.7 Delamination mechanism during composite drilling process, (a) Peel-up delamination at entrance, (b) push-out delamination at the exit (Ismail *et al.*, 2017).

2.7 Tool wear

Tool wear is an unwelcome occurrence in the machining process. This is because the cutting tool is facing gradual failure as the cutting tool have loses a certain amount of material due to frequent usage in machining. It has an impact on the drilled surface (hole) quality and the geometry of the material workpiece. Abrasive dry powder is created during the drilling of carbon composites. The inefficient extraction of these chips cause the tool wear rate to become high. Types of wear such as flank wear and crater wear usually occurs when the tool's section is in contact with the completed component erodes. The most frequent type of wear occur is the crater wear. Crater wear was produced to a major extent due to excessively high local stress imposed on the cutting edge. Hence, cause discontinuous chip formation at the tool rake face when drilling at high thrust force with high temperature due to continuous friction applied between the cutting tool and the specimen. This lead to condition such as tool flagging which propped up cutting edge chipping. (Madhavan and Prabu, 2012).

Besides, continuous friction during drilling between cutting tool and CFRP panel also can contribute to rapid tool wear and also can cause the epoxy on the specimen’s surface to be burn when drilling at high temperature (Liberati *et al.*, 2018). The anisotropic and non-homogeneous characteristics of CFRP also making the drilling operation to become more complex as there is the existence of hard carbon fibers in CFRP. In the end, result to rapid tool wear which can give impact on the hole quality produce called as delamination. Abrasive wear, adhesion, and chipping are all factors that contribute to tool wear in composite laminate drilling. Mechanical wear is another term for abrasive wear. As the major tool wear element in drilling composite laminates, it is largely caused by the great wear resistance of carbon fibres (Lee, Ge and Song, 2021). Workpiece deflection and drill bit fracture occurred when the cutting force increases with the workpiece-drill tool interface temperature. Thus, contribute to rapid tool wear while at the same time degrade the internal structure of the composite which can lead to epoxy burn as the result of continuous friction between cutting tool and the workpiece. Drill tool wear increased proportionally as thrust force, torque on the drill bit, and the number of drilled holes (انیم گردچ, 1369).

From the literature review, the observation of wear was focus at the sharp edge of the fresh uncoated drill before drilling. By referring to Figure 2.8, there is no micro fracture or chipping observed on the rounded tool edge even though after drilling several holes. The Scanning Electron Microscope (SEM) image show smooth image of an uncoated carbide drill was spotted at 500 magnification. This reflect that the Co binder was removed from the cutting tool after drilling for several periods causing exposure of the carbide grains. Carbide grain dislodging was spotted on rake and flank surfaces indicate that a lot of carbide grains was pulled out from the tool surface after drilling (Wang *et al.*, 2013).